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Modeling Reservoir Formation Damage due to Water Injection for Oil Recovery

Abstract
The elliptic equation for non-Fickian transport of suspension in porous media is applied to simulate the reservoir formation damage due to water injection for oil recovery. The deposition release (erosion of reservoir formation) and the suspension deposition (pore plugging) are both taken into account. 1-D numerical simulations are carried out to reveal the erosion of reservoir formation due to water injection. 2-D numerical simulations are carried out to obtain the suspension and deposition profiles around the injection wells. These preliminary results indicate the non-Fickian behaviors of suspended reservoir fines and the corresponding formation damage due to erosion and relocation of reservoir fines.

Introduction

The migration of reservoir fines may give rise to severe permeability damage and oil productivity decline. This phenomenon has been widely observed in petroleum industry [1-7]. There is a considerable and ongoing effort aimed at understanding release of reservoir fines, particle transport, and caused formation damage.

The release of reservoir fines may be caused by change of water chemistry, hydraulic drag, and reaction between the acid in water and the reactive mineral of porous media [8-17].

A porous medium is "water-sensitive" if its permeability is dependent on the chemistry of the flowing fluid. The causes are believed to be in situ swelling of clay and migration of reservoir fines due to the change of water chemistry. It has been observed that injecting water of low salinity into a saturated sand core of high salinity leads to the reduction of permeability owing to the migration and the redeposition of clay [12, 18]. There exists a critical salt concentration (CSC) below which the clay starts to release. The clay detachment due to this mechanism is usually fast, while the available amount of clay for release at the specific salinity is limited. Multiple CSCs have been observed for different types of clay in the same porous medium [18].

Another mechanism for particle release is the hydraulic drag from the flowing fluid [8, 19-22]. When the viscous torque from the flowing fluid is larger than the adhesive torque along the pore walls, the attached particles start to depart. The process is strongly affected by pore structure, the local flow rate, the particle size and the adhesion mechanism. Induced detachment can be significant at high flow rate and recover the permeability to some extent [16, 23]. Numerous works focus on the corresponding permeability damage [7, 12, 14-17] whilst only a few studies on the transport of the reservoir fines [9, 18].

The transport of reservoir fines in porous media is usually described by a parabolic advection dispersion equation (ADE) with a sink term representing the deposition and a source term representing the release of particles [8, 22, 24-27]. For the cases without particle release, the classical methodology can merely catch stepwise symmetric breakthrough curves and predict exponential deposition profiles. On the other hand, a growing body of experiments shows that the deposition profiles may be hyperexponential or even nonmonotonic [28-36]. In artificially heterogeneous porous media and natural porous media the experiments may result in dispersed breakthrough curves of the non-Fickian type (asymmetric with early arrivals or large tails) [32, 37-41].

It is believed that the heterogeneity of the particle population is the main reason for hyperexponential deposition profiles in homogeneous porous media [40-45]. The heterogeneity of the particle population encompasses the physical heterogeneity (size and shape) and the physiochemical heterogeneity (surface charge and multiple energy minima). Even flow of a monodisperse suspension (uniform shape and size) in a homogeneous porous medium under unfavorable attachment conditions is observed to result sometimes in a hyperexponential deposition profile, due to the heterogeneity of particle surface charge and second energy minimum [28, 29]. Mathematically, the heterogeneity of the particle population is described by the distribution of the filtration coefficients. The deposition patterns may be interpreted by application of various distribution types: the log-normal distribution, the power law distribution, the bimodal distribution and others [28, 30, 34, 44]

Besides the heterogeneity of the particle population, the media heterogeneity in connection with the non-Fickian transport may also lead to hyperexponential deposition [44, 46]. Recent works indicate that non-Fickian transport of a solute or a suspension may be modeled more accurately by approaches based on the continuous time random walk (CTRW) theory compared to the classical advection dispersion equation (ADE) [44, 46]. In the framework of the CTRW approach A. Shapiro and P. Bedrikovetsky proposed a macroscopic elliptic equation for non-Fickian transport in porous media [47, 48]. Recently, this approach has been extended in order to incorporate the distributed particles, as well as plugging of the porous medium [27, 44, 46].

Compared to the conventional ADE the elliptic equation has two additional terms reflecting the distributed residence time or flight time of the particles: the temporal dispersion term and the mixed dispersion term. In cases where the particles of n different types are filtered in a porous medium, n elliptic equations (plus deposition-plugging equations) are required for description of the filtration.

Neither the particle population heterogeneity in connection with the distributed deposition and release rates, nor the median heterogeneity in connection with the non-Fickian transport has been considered in the convection models for the release of reservoir fines. The elliptic methodology has been proved to excel the conventional ADE in both modeling the dispersed breakthrough curve and the hyperexponential deposition [44]. It has not been applied in the system with both particle release and particle deposition, either.

Elliptic Model

The elliptic equation for particle transport, release and deposition in porous media is adopted for modeling the formation damage around the injection wells in oil reservoirs. Details can be found in previous works [44, 45].

Implementation

The basic calculations are carried out in FORTRAN. Some of the results are illustrated in MATLAB and COMSOL Multiphysics. Finite element methods (2nd order) and finite difference methods (central difference scheme) are applied to transform the elliptic partial differential equation into an algebraic equation. Gaussian elimination with partial pivoting for sparse matrices is performed to solve the algebraic equations numerically.

Results

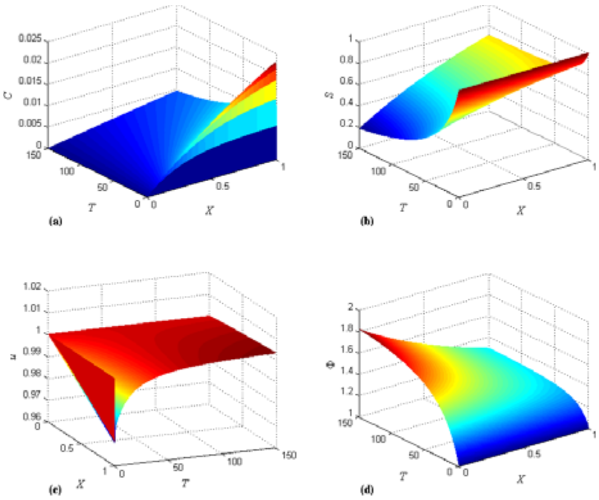

Figure 1: Modeling results for 1-D erosion of porous media due to water injection, (a) suspension concentration, (b) deposition, (c) velocity, (d) porosity

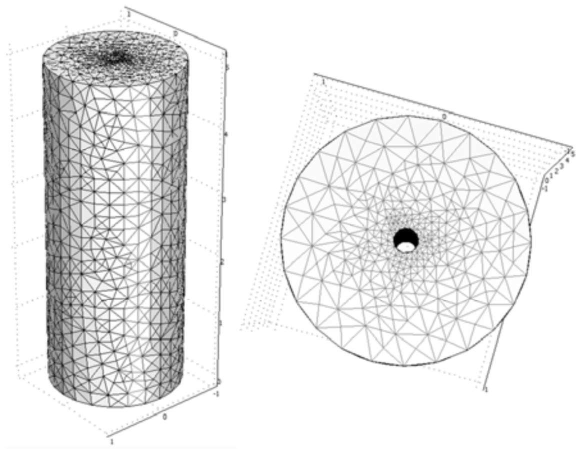

Figure 2: Illustration of the mesh for an injection well in oil reservoir

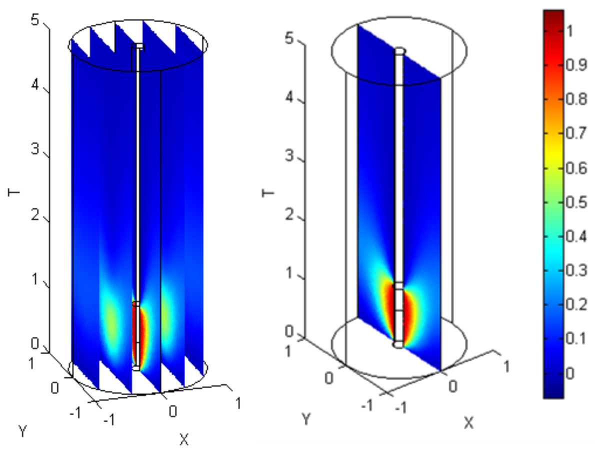

Figure 3: Suspension injection in oil reservoirs

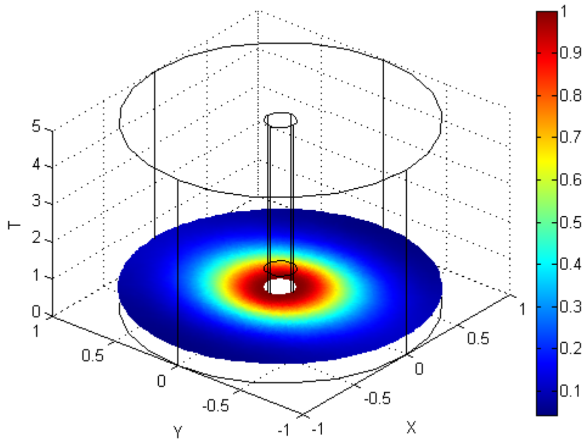

Figure 4: Horizontal cross-section around the injection well

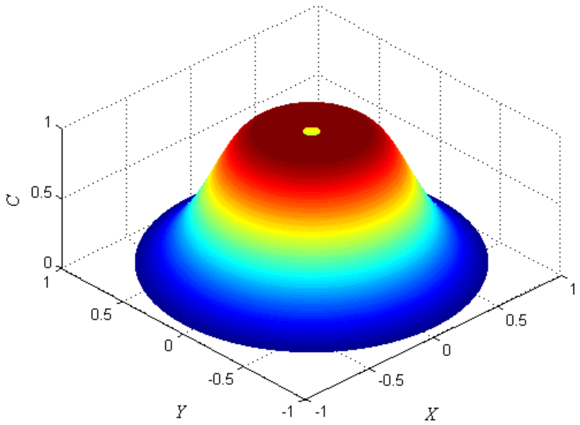

Figure 5: Suspended concentration profile at T=0.5

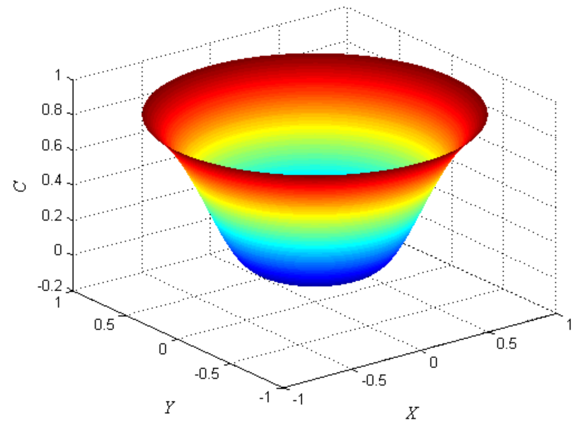

Figure 6: Suspended concentration profile at after injection T=2.5

Modeling results for 1-D erosion of reservoir formation are obtained, as seen in Fig. 1. The release of deposited particles are flushed out of the system, and recaptured by the porous media. Complete pore plugging mechanism is also taken into account. It can be seen that the erosion is stronger close to the inlet of injection since the porosity is lower.

2-D modeling for the formation damage around the injection wells is carried out, as seen in Fig. 2. The injection well lies in the center of a pie of reservoir. It is worth mentioning that the 3rd dimension is time. The injection follows a pulse injection procedure, i.e. suspension injection till T=1 and water injection till T=5. The concentration profiles are revealed in Fig. 3 to Fig. 6.

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